Decision Support Systems and Processes for Groundwater

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Abstract

Information and knowledge management challenges abound in groundwater sciences. Groundwater problems of interest to society are characteristically complex and exceed our ability to solve them without the aid of computational analysis. Yet discipline specific problems that are of interest to hydrogeologists frequently do not directly address the immediate decision making needs of policy makers, groundwater managers, and stakeholders. It is the immediate societal needs that drive the demand for science-based information for common problems in which groundwater figures as a prominent element. Integrated Assessment and Modeling (IAM) presents an approach for merging discipline and case-specific knowledge, such as those in hydrogeological sciences, with social drivers for use in decision support applications. Moreover, decision support systems (DSS) that are constructed and applied using integration as a guiding principle and design ethic can advance groundwater DSS beyond passive support toward active and, eventually, proactive support for implementations to achieve real world integrated groundwater management.

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25.1 Introduction

Groundwater is a critical water resource that must be managed effectively while meeting the demands of society. The behavior and response of groundwater systems to natural and human influences are best understood through scientific analyses using data and models. In groundwater resource management, as with all water resources, disputes can be compounded by misconceptions about the meaning of data and scientific models, as well as social and political misunderstandings among the various interests. The complexity of groundwater management creates the need for computational assistance to support reasoned consideration of available scientific knowledge in conjunction with the preferences of the resource users.

Decision support systems (DSS) are computational systems that use data and models interactively to aid in the formulation, analysis, and selection of management strategies. The design, architecture, and implementation of DSS are extensive, highly variable, and, ultimately driven by the needs of the decision problem and instance that is under evaluation. At the simplest levels, DSS may provide repositories of data and information in accessible formats and could offer tools to search and discover repository content. At the other end of the spectrum, DSS may incorporate sophisticated simulations, link with optimization algorithms, or other intelligent systems components to enhance decision making. Regardless of the level of sophistication, DSS are well suited for application to integrated groundwater problems because they can provide a set of applications, methodologies, and tools to cope with the inherent complexity and uncertainty. They can also be part of an Integrated Assessment and Modelling (IAM) process (Jakeman and Letcher 2003) providing distinct advantages for facilitating the IAM process, its transparency and its legacy. Indeed if constructed appropriately, DSS can provide ways of exploring and explaining tradeoffs, provide a tool for adoption and adaptation, create a repository to document the project methods, archive a library of integrated data sets, models, methods, visualization and other tools, a focus for integration across researchers and stakeholders, and act as a training and education tool (Jakeman and Letcher 2003). While the use of DSS for groundwater problems poses potential for improved outcomes, in practice DSS technologies are rarely implemented.

Conceptually, the use and adoption of DSS for groundwater is straightforward. Yet the adoption of DSS may be limited due to scientific, social and technical challenges (McIntosh et al. 2011). Groundwater decision support combines collections of scientific data and models that are inherently uncertain, so that drawing robust recommendations for policy or management is difficult. The creation of DSS is also a multi-disciplinary process that engages subject matter expertise with stakeholder interests across a wide range of sectors in society. Framing DSS applications so that the inputs and outputs are relevant for multiple perspectives is an added hurdle between theory and practice. While the level of effort for developing hybridized computer architectures for DSS is decreasing, the length of time, costs, and computational intensity remain barriers to regular use for groundwater.

This chapter evaluates the state of DSS applications that incorporate groundwater modules with the aim of informing researchers and practitioners interested in designing, developing, and deploying DSS for use in integrated groundwater management.

25.2 Decision Support Systems in Relation to Groundwater

Population is increasing around the globe with over 9.5 billion individuals projected by 2050 (United Nations 2010). The concomitant water resource demands for these 9.5 billion water users are expected to lead to disputes over the finite global water supply. To address future water demands, groundwater science needs to provide adequate characterization of the physical systems to assure that policy limits, and management strategies for water allocation are feasible. Simultaneously, scientists and managers need to incorporate the concerns and priorities as defined by stakeholders and the policy context for any aquifer early in design and assessment of options. In effect, knowledge related to both aquifer performance and groundwater governance needs to be explicitly provided in usable formats, such as DSS, in order to achieve integrated groundwater management (Pierce et al. 2013).

Integrated methods that incorporate considerations beyond hydrogeologic analyses using a strict disciplinary focus can be employed to assess the factors of aquifer management or policy defined by both science and consensus conditions (Pierce et al. 2013). The continuum view of aquifer yields (Pierce et al. 2013) fits within an integrated water resources management approach to groundwater science and lends itself to decision support applications. It also requires an adjustment to the underlying framework hydrogeologists use to describe and categorize types of yields. Every DSS is built using datasets and models that represent the problem domain and key elements of interest to decision makers and stakeholders. Building on the concept of interrelated knowledge processes, Fig. 25.1 highlights the relationship between decision

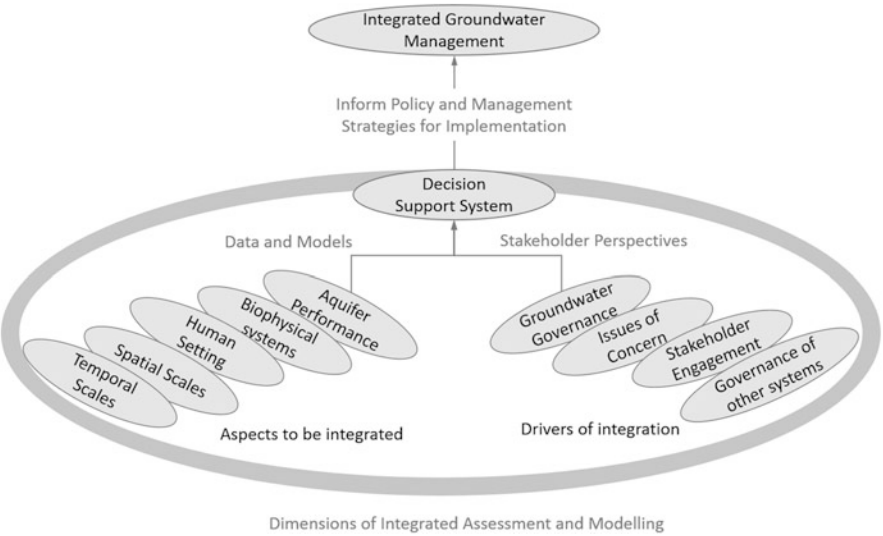

Fig. 25.1 The conceptual relationship between decision support, aquifer performance, and groundwater governance in integrated groundwater management (Modified from Hamilton et al. 2015; Pierce et al. 2013)

support and the knowledge processes of aquifer performance and groundwater governance. It depicts an expanded scope of DSS for applications in integrated groundwater management by combining framing elements from hydrogeological sciences and an aquifer continuum approach (Pierce et al. 2013) and the primary dimensions of IAM (Chap. 1 and Hamilton et al. 2015).

Beyond the content, disciplinary expertise and relationship among the interacting parts of a DSS process, the type of support can vary from informative to normative. The targeted approach distinguishes between providing access to explanatory or analytical information about a decision problem (informative) versus approaches that provides guidance on candidate solutions (normative). This distinction is a factor in determining the selection, incorporation, and interaction with the scientific information and knowledge that becomes part of the DSS build for each application.

25.2.1 Aquifer Performance

Science-based decision making depends upon an acceptable understanding of groundwater systems. Hydrogeology describes aquifers and groundwater flow principally through the use of data and models. Aquifer performance factors reflect physical processes commonly assessed through geological observations, and field measurements of flow conditions that are encoded and integrated into simulation models by subject matter experts (Pierce et al. 2013). Groundwater science has made significant strides towards measuring, describing and quantifying the nature of aquifer behavior. Some traditional hydrogeological methods for measuring or estimating groundwater parameters (see also Chap. 3) include water budgeting, numerical modeling, optimization, simulation, chemical tracing, chemical mixing models, flow-net construction, pump testing, slug testing, and geophysical methods (Weight and Sonderegger 2001).

Field observations and the principles of flow that are used to evaluate groundwater response also provide a set of natural attributes that are common to hydrogeologic problems. Hydrogeologic attributes (shown in Table 25.1, Sect. 25.3.1 of this chapter) are the most basic unit of information for describing groundwater systems. As such, hydrogeologic attributes form the cornerstone elements in an ontology for groundwater decision support. Ontologies are formal representations of knowledge. The set of vocabulary, concepts, and the relationships between them are defined within a domain. In this case, the hydrogeology domain has established a set of information within an ontology to describe how groundwater systems function. A first step towards designing, developing, and using hydrogeological information to support decisions depends on identifying what kind of information and knowledge is necessary to describe the problem adequately. Physical system attributes for groundwater are the first necessary elements. A secondary set of necessary elements includes the considerations related to stakeholder concerns and revolves around the topic of groundwater governance.

Table 25.1 Natural attributes for a hydrogeologic system[a]

State conditions	Inflows	Storage	Outflows	Model considerations[f]
Aquifer type[b] (m)	Natural recharge spatial component [R_n(x, y)]	Specific storage (S_s)	Natural discharge spatial component [Q_n(i,j)]	Planning Horizon (g)
Boundary conditions[c]	Natural recharge rate [R_n(t)]	Saturated thickness (b)	Natural discharge rate [Q_n(t)]	Stress Period (p)
Areal extent of aquifer[d] (A)	Artificial recharge spatial component [R_a(x, y)]	Storage (S_T)	Pumping well spatial component [Q_a(i,j)]	Time Step (t)
Porosity (ø)	Artificial recharge rate [R_a(t)]	Specific yield (ϕ_{eff} or S_y)	Pumping well discharge rate [Q_a(t)]	Cell (i,j,k,z)
Hydraulic conductivity (K)	Return flow (α)[e]	Storativity [−]	Evapotranspiration [Q_e(t)]	Zone (z)
Land Surface Elevation (m_{ij})	Lateral or vertical influx (V)[e]	Hydraulic head [h(x,y,z)]	Lateral or vertical outflux (V)[e]	Bottom confining unit elevation (n_{ij})
Drain elevation (d)	Unrecoverable Storage (S_u)	Minable Storage (S_m)	Replenishable Storage (S_r)	Diffusivity[g] (T/S)
		Transmissivity (T)		Acceptable variance (X)

Notes:
[a]Table excerpted from Pierce 2006 showing a list of influential hydrogeologic parameters as indicated by Feinerman and Knapp 1983; Gisser and Sánchez 1980; Bredehoeft and Young 1970; Freeze and Massmann 1990; Alley et al. 1999; Kresic 1997; Harbaugh and McDonald 1996; Kalf and Wooley 2005 – this list is not necessarily comprehensive
[b]Such as fractured/porous; consolidated/unconsolidated; stratigraphic position and extent (after Freeze and Massmann 1990)
[c]Conditions can include no flow boundaries (lateral), surface impermeabilities, constant heads, differences between geologic units, etc.
[d]An areal extent may be subdivided into zones of confinement, unconfined, and artesian
[e]Return flow and lateral influx or outflux can be counted within the artificial or natural recharge and natural discharge components respectively or split apart as separate components of recharge to the system as shown here
[f]Presented in the context of finite difference modeling, such as in MODFLOW packages
[g]Diffusivity is an indication of the rate of movement through a system and the capacity to sustain localized drawdowns without resulting in long-term storage depletion. An aquifer's diffusivity is probably a good indicator of the relationship to an appropriate planning horizon

25.2.2 Groundwater Governance

Management of water resource demands requires the incorporation of legal and regulatory rules for allocation (Part II of this book) as well as community preferences for risk sharing of the potential consequences of water shortages. In short, the interdependency of community drivers and science-based analyses must be recognized and integrated to determine the actual availability of a resource under various management policies as depicted in Fig. 25.1.

Aquifer governance includes the social and contextual aspects of a case that may be used by groundwater managers, together with operational definitions, to implement management regimes (Pierce et al. 2013). Participatory processes are one of many stakeholder engagement and modelling approaches that are well suited for unravelling the issues of aquifer governance. A review of design methodologies, approaches, and guidance on common stakeholder modelling techniques and typologies are discussed broadly in the literature on decision support processes and stakeholder engagement (e.g. Voinov and Bousquet 2010; Margerum 2008). Combining scientific knowledge with stakeholder perspectives, preferences, and concerns generates opportunities to (1) address misconceptions about the science content, (2) establish a shared learning and visioning environment, and (3) increase the likelihood of adoption for solutions that may be identified. DSS offer mechanisms and methods for merging a plurality of views and information that are needed to achieve effective groundwater governance and reduce the potential for conflict.

25.2.3 Decision Support Systems and Processes

The use of DSS represents a systematic approach to often divisive and intractable issues, such as groundwater availability and its allocation. Defined as interactive computer models, DSS incorporate data relative to a problem and, through programmed analyses, aid the formulation and selection of an appropriate management strategy. The development of a DSS is inherently systemic and multi-disciplinary which differs from traditional analytical approaches that are discipline specific and tend to isolate variables. In addition, the design and development of DSS benefit from engagement and participatory inclusion of stakeholders and decision makers.

Research into the behavior of decision makers demonstrates that the complexity of many decision problems quickly outstrips a decision makers' unaided cognitive capacity (Gregory et al. 2005). Complex socio-technical decisions, such as those needed for groundwater management, are based on large quantities of evidence that is frequently assembled and analyzed by multi-disciplinary teams. The meaning and implications for developing management strategies or actions are evaluated and compared through the eyes of stakeholders. DSS that combine aquifer performance and groundwater governance, as shown in Fig. 25.1, create a more transparent lens through which complex groundwater problems may be viewed without overwhelming stakeholders.

Decisions about aquifer yields are the most common to groundwater problems, though a wide range of other common decision making contexts exist. A non-comprehensive list of examples includes decisions about groundwater availability, such as defining acceptable pumping limits, pump locations, or determining the influence of pumping on threshold flows for groundwater dependent ecosystems (Chap. 15). Another segment of decision contexts include groundwater quality decisions (Chaps. 14 and 15), such as those related to remediation and risk prevention. And decision contexts related to groundwater monitoring stations, sampling locations, or waste management are all good examples of the numerous sets of decision contexts that cross sectors, from industrial to environmental management or domestic and agricultural use cases.

The following sections delve into a more detailed discussion of performance, governance, and decision support elements as they relate to groundwater applications.

25.3 Data and Modeled Attributes for Aquifer Performance

Information and knowledge management challenges abound in groundwater sciences. Every DSS is built using datasets and models that represent the problem domain and key elements of interest to decision makers and stakeholders. The domain of hydrogeology is comprised of significant data collections that span spatial and temporal scales across many orders of magnitude with variable resolutions (Narasimhan 2005).

While the scales and extent of groundwater information are vast, the datasets often are sparse considering the complexity in the systems. The resultant uncertainty, paired with inherent variability in groundwater systems limit the predictive value of groundwater models that form the core of decision support systems (Chap. 28). Regardless, offsets of parameters are derived from direct measurements and field observations to quantify and describe groundwater system behavior. These data are used by groundwater modelers to populate, extrapolate, and define a numerical simulation to represent the natural behavior of aquifer systems. Modeled outputs then form the core information for any undertaking in integrated groundwater decision support.

While groundwater modelers are concerned with the low predictive value of numerical simulations for aquifers, from a DSS perspective the focus revolves around (1) linking groundwater with ancillary components in the integrated models (e.g. land use, climatic conditions, and surface water, etc.), and (2) communicating the level of uncertainty as it relates to the decision context.

25.3.1 Natural Hydrogeologic Attributes and Uncertainty

Identifying natural attributes of a groundwater system is a vital step in determining a method for calculating relevant performance indicators for decision contexts related to both groundwater response and linkages with ancillary or related aspects for integration.

Parameter uncertainty is a key consideration for assuring that the representative groundwater model reflects actual aquifer behavior. Hydrogeologists have established a myriad of approaches for addressing uncertainty with domain-centric groundwater models (Matott et al. 2009; Banta et al. 2006; Doherty and Skahill 2006; Doherty 2003, 2004; Hamby 1994; Hill 1998; Poeter and Hill 1998). Yet direct assessment and treatment of uncertainty as it relates to integrated groundwater models, such as those that inform DSS applications are less common and recent (Guillaume et al. 2012; Guillaume and Pierce 2011). Integrated modelling is beginning to establish methods and approaches to creating and testing IAMs (e.g. Bennett et al. 2013) and groundwater modelling practice reflects these advances. A key issue is the problem of the low predictive value of groundwater models, particularly when they are combined within an IAM, and the central element of concern is related to the variables and parameters that are used to define the systems of interest, or the attributes. The measurements used to describe and monitor a groundwater system serve as the basic units of knowledge that define performance for decision problems. A natural attribute, defined by Keeney (1992), is a measurable quantity or criterion that has a common interpretation and can indicate the level of achievement of goals or objectives. A review of natural attributes that are common to hydrogeologic problems, compiled by Pierce (2006) and shown in Table 25.1, reveals approximately 37 measures, variables and descriptive parameters.

The units of information shown in Table 25.1 are central to an ontology and scientific understanding of groundwater, as well as being core to the design of groundwater-related decision problems. For example, defining an actual rate of yield or extraction rate, along with primary natural attributes, must begin with the master equation for hydrology, where changes in storage (S) over time (t) can be defined as the difference between inputs (such as recharge) [I(t)] and outputs (such as discharge) [O(t)]. Determining the response of an aquifer to variations in any one of the variables for this equation is key to defining the volumes of groundwater that may be available for extraction. In turn, defining groundwater availability is a quintessential hydrogeology decision problem (Pierce et al. 2013) that may be bounded by limiting constraints for population growth, water demand, and total use of the resource for example.

Natural attributes provide the cornerstone for quantifying and valuing groundwater resources and for developing integrated groundwater management strategies. The natural attributes also serve as the parameters that represent groundwater response in simulation models. Collecting the information needed to understand and model groundwater systems is a necessary first step to decision support.

A DSS links together raw data, empirical calculations, numerical models, and other qualitative factors to analyze decision problems. DSS can help decision-makers conceptualize a problem in a new way, as well as allowing for the rapid conversion of the vast sets of data typically associated with groundwater problems into understandable reports that can provide guidance and insight (Kersten 2000).

25.4 Addressing Stakeholder Perspectives for Groundwater Governance

While a great deal of data may exist to inform appropriate analytical or numerical analyses for groundwater resources, the ultimate influences of scientific uncertainty and the issue of complexity require the inclusion of stakeholder perspectives and concerns. Moreover a primary problem as far as DSS is concerned is the communication of this uncertainty to stakeholders and decision makers. The value-based considerations that can only be gleaned from interactions with stakeholders must guide the identification and prioritization of management options that fit with available scientific knowledge and social concerns. In fact, modeling efforts that engage qualitative methods and stakeholder input tend to create more informative problem formulations than traditional efforts without stakeholder advice (Li et al. 2013). These participatory processes are frequently referred to as a co- design and co-creation approach.

Decision support provides a mechanism that interactively bridges the theoretical and methodological gaps between physical systems, analytic outcomes, knowledge interactions and interfaces with users, as well as providing computational support for science-based exploration, dialogue, and/or deliberation. Research on applied, participatory, decision support recognizes that science dialogue is simply another means of communicating ideas or knowledge (Welp et al. 2006) and provides rich qualitative inputs for modeling of complex problems.

Application of fundamental scientific and engineering principles alone can identify a set of management alternatives that are efficient across a number of performance metrics. Yet, technically sound solutions may, in fact, yield options that lead to an unacceptable political price (Allan 1999) because without the aid of a decision support process they neglect social values and process. The Murray-Darling River Basin provides a real world example where farmers protested a technically sound water plan that was unveiled by the Australian Government without adequate stakeholder consultation (Sullivan 2014). Therefore, approaches that recognize the difference between the measurable components of physical systems and the underlying values and preferences that influence management decisions are also needed. Clearly delineating the objective components of a problem from the value-based, or subjectively-judged, components is crucial to assure a final set of decisions that can be implemented without exacerbating disputes (Focazio et al. 2002). For example, a strategic path forward might include efforts to strengthen institutional capacity for managing over-pumped groundwater resources in order to prevent irrevocable damage to an aquifer system. Such governance depends on effective communication with, and advice from, stakeholders and water users.

Effective communication about decision problems follows a recognized set of conventional stages (Mintzberg et al. 1976):

1. Problem formulation or definition
2. Identification of decision objectives
3. Generation and analysis of options
4. Choice of a preferred option
5. Implementation
6. Monitoring and feedback
7. Iteration and problem redefinition.

Groundwater decisions frequently involve a distributed set of stakeholders who need assistance to work through the various stages of decision making and DSS may be of assistance at any of these stages or for multiple stages. Decision support for groups includes processes that enable cooperation among decision makers and stakeholders, while assuring that each participant has a clear stake in the problem that needs to be solved and guides the group towards a shared vision.

Processes may range from informative to strongly normative approaches. Informative approaches attempt to improve the quality of a decision by providing information to help decision makers analyze a situation and assess alternatives. Normative support aims to recommend options based on expected outcomes, rather than strictly explaining information or knowledge.

Regardless of the approach, there is broad agreement that successful processes engage participants and build capacity (van Kerkhoff and Lebel 2006). Consensus building remains the dominant process for creating a shared vision with participatory engagement. Systems thinking (Chap. 24) frequently informs the development of group goals, targets, and criterion. In the context of groundwater governance, consensus yield is a concept that is used for the most common decision making context for groundwater whereby the acceptable range of extraction from an aquifer is bounded by the preferences of affected stakeholders (Pierce et al. 2013; Mace et al. 2001). Consensus yield has become a recognized concept within hydrogeology, yet there are many instances and decision contexts, as discussed previously, where decisions about groundwater and the systems that are naturally linked, or integrated with aquifers, are aided by DSS applications. The preference sets and prioritization of candidate solutions then defines a feasibility space within which technically viable strategies for operational yield and management can be designed. Figure 25.2 shows a conceptualization and example of mapping aquifer performance with the overlay of stakeholder preference points to define a feasible solution space (modified from Pierce 2006). It depicts the intersection between the integrated system response measures, or performance metrics, as generalized groundwater storage response to pumping, and defines the feasibility space.

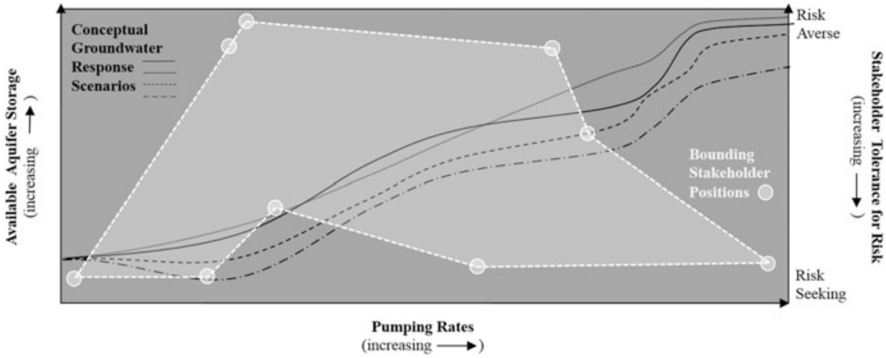

Fig. 25.2 Conceptual mapping of a feasibility space as defined by hypothetical aquifer performance across multiple scenarios bounded by hypothetical stakeholder preference points (Modified from Pierce 2006)

Framing the problem is a pivotal aspect for capturing principle stakeholder concerns, as well as defining the initial terms of focus for negotiation or deliberation (Chap. 24). Bridging the gap between problem formulation stages and groundwater model development provides an area with potent research potential and opportunities to improve the applicability of research products to real-world groundwater management problems (Borowski and Hare 2007).

25.5 Decision Support Systems: Background and Types

As research related to science-based decision making has evolved, increasing levels of insight and understanding are expected to be generated from the application and use of DSS. The field of decision support is constantly advancing at the boundary between theory and application. Theoretically DSS research begins with the premise that improving knowledge management will result in superior outcomes for decisions. For that reason, DSS development activities that target improvements in knowledge management are expected to foster meaningful advances when the DSS are deployed in practice.

Proponents of DSS further claim that activities striving for the most advanced levels will achieve effective knowledge management leading to the generation of 'new' knowledge. The history of DSS development provides a foundation from which to create concrete applications in a specific domain. In assessing DSS case studies that include groundwater, it becomes clear that the level of effort for applying DSS knowledge is significant even while we are able to preview from the broader DSS literature what future advances may achieve.

25.5.1 The Emergence of Decision Support

While some practitioners credit Simon (1960) with the presentation of basic management decision processes, Little (1970) was the first to define a DSS as part of the concept of decision calculus. The first international conference on DSS was held in Atlanta, GA in 1981 (Power 2003). DSS literature recognizes that DSS models are simplified representations of problems addressed within a society that assist with the development and evaluation of alternatives. They use multi-objective planning to simultaneously consider various aspects of the decision-making paradigm (Haith and Loucks 1976), such as environmental quality, optimization, and economic cost-benefit analyses.

Since the inception of DSS, theories and applications have evolved to ever more sophisticated approaches over time by leveraging technological advances and transitioning toward improved functionalities and applied competencies on a case-by-case basis.

In the context of groundwater science and governance, the epitomy of groundwater DSS applications will communicate the extent and influence of scientific uncertainty while also enabling interactive deliberation among a plurality of stakeholders. In effect, an idealized DSS for groundwater will provide an advanced level of negotiation and facilitation support. Progressing from fundamental DSS applications to a full DSS with the capability to support live negotiation among groups of stakeholders requires a series of transitions that have been characterized by Kersten and Lai (2008). The progression of DSS types, depicted in Fig. 25.3, identifies transitions among DSS types that range from passive to active, and ultimately proactive applications with the relative level of effort that is necessary

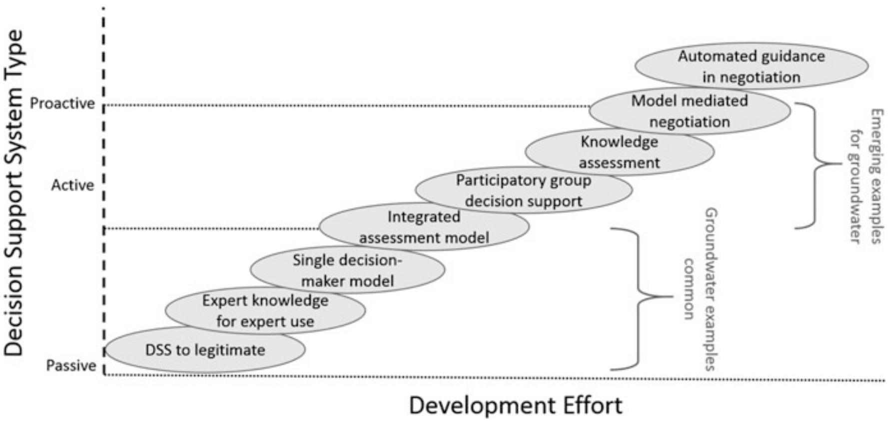

Fig. 25.3 Evolution of decision support systems for proactive support of science-based deliberation and negotiation (Modified from Kersten and Lai 2008; Pereira and Quintana 2002)

for development, (modified from Kersten and Lai 2008; Pereira and Quintana 2002). The concept of DSS types and tiers (Kersten and Lai 2008) is helpful for assessing the state of use in groundwater cases. The following sections describe the DSS types and evaluate the state of groundwater DSS through this lens.

25.5.1.1 Passive

Passive DSS are tools that aid communication, calculation, and visualization in direct response to the input of a user. These systems augment users' ability to interact or analyze information, but interactivity is limited to direct selection and specification by a user (Kersten and Lai 2008).

The majority of groundwater modeling and management applications reported in the literature can be considered passive type systems from a DSS perspective. Case examples for integrated assessment that include groundwater are beginning to emerge (for example see various cases listed in Table 25.2), with the most advanced case studies transitioning from passive to active style applications.

25.5.1.2 Active

DSS assistance that helps users formulate, evaluate, and solve difficult problems is considered an example of an active system. Active systems provide utilities that support construction and processing of solutions for users (Kersten and Lai 2008). Active DSS may include some automatic knowledge capture or search techniques.

Integrated models and assessment provide the transitional DSS type between passive and active. Jakeman and Letcher (2003) discuss the basic features of integrated assessment models (IAMs), yet little consensus on a generalized framework for the use of IAM's within decision support contexts has been achieved (van Evert et al. 2005; Mysiak et al. 2005). Various approaches and frameworks are presented in the literature (Villa 2007; Khaiter 2005; Moore et al. 2004; Rahman et al. 2004; Sydelko et al. 2001; Argent and Grayson 2003; Segrera et al. 2003; Leavesley et al. 2002). They range from: generalized modeling frameworks that are more accessible to non-programmers but limit specific model implementation; to model-specific frameworks, or implementation-level frameworks, that require a higher level user group, usually with programming experience and result in increased development effort.

25.5.1.3 Proactive

Systems that can evaluate aspects of a decision problem independently with the ability to provide feedback to facilitators/mediators and users during a negotiation process are proactive. These systems are similar to active systems with the addition of facilitator and mediator centric utilities, as well as algorithms with embedded assessment of user inputs in order to derive, or recommend, alternative options. Proactive DSS are expected to provide capabilities to aid group facilitation or mediation, along with the ability to access and use information in real time for the purpose of supporting the facilitators or negotiators. Proactive systems will make suggestions and critiques for improving the outcome of a DSS supported deliberation or negotiation.

Table 25.2 Decision support or analysis projects with groundwater features

Source	Problem	Scale	GW Simulation	Optimization & larger DSS	Objective function	Decision variables
Fienen et al. (2013)	Forecasting changes in sea level rise and groundwater		SEAWAT model aggregated to Bayesian network	Bayesian network to emulate groundwater response/uncertainty	Propagate uncertainty efficiently for use in forecasts for decision makers	Focus on model performance and calibration; decision model not developed
Molina et al. (2013a)	Evaluating climate change impacts over time	Regional: Serral-Salinas aquifer, Spain	Used Post-process to evaluate groundwater response; MODFLOW model	Scenarios tested with an Object Oriented Bayesian Network (OOBN)	Comparative analysis across scenarios and time windows; Extensive list of performance measures based on : Agricultural net profits and aquifer storage; Maximizing Total income, employment rates	Intervention actions, such as water rights purchase, land sale, sale of water for irrigation,
Hadded et al. (2013)	Water management generally	Local to Regional: Zeuss Koutine aquifer, Tunisia	MODFLOW	WEAP-MODFLOW link	Demand satisfaction, cost and drawdown minimization	Limited by salinity levels and flow capacity
Molina et al. (2013b)		Regional: El Salobra aquifer, Spain	Lumped parameter representation of the aquifer within a linked hydro-economic model	Object Oriented Bayesian Network (OOBN) for stochastic modeling	Assess groundwater quality control with uncertainty; Minimize nitrate concentration and recovery times	Fertilizer quotas Fertilizer prices
Le Page et al. (2012)	Water allocation	Regional: Haouz-Mejjate plain, Morroco	MODFLOW	WEAP-MODFLOW link	Evaluate impacts to regions and identify mitigation options	Principally used to validate modelled aquifer response and sensitivities to parameter change

Moura et al. (2011)	Assess groundwater quality control with uncertainty	Local to Regional: farm and aquifer for case studies; Upper Guadiana Basin; Altiplano, Spain	Lumped parameter representation of the aquifer within a linked hydro-economic model	General Algebraic Modeling System (GAMS) and Object Oriented Bayesian Network (OOBN) for stochastic modeling	Maximize gross margin at the farm level as a function of crop prices and yields; the OOBN added response levels in groundwater	Crop surface Irrigation method Soil type
Triana et al. (2010)	Evaluate feasibility and performance of water mangemetn strategies	Regional; Lower Arkansas River Basin	Canal seepage and infiltration to groundwater estimated from a MODFLOW/ MT3DMS simulation	Based on River GeoDSS with an Artificial Neural Network (ANN) used to distribute recharge to groundwater	Comparative analysis of estimated performance with a prioritization structure based on performance with Total Storage Water shortages Compliance with legal compact Impacts to water quality	Water strategy choices include: Total water diverted Use of storage Weighting of priorities (shown in Objective column)
Van Cauwenbergh et al. (2008)	Ranking alternative water management options with multi-criteria	Local aquifer to regional watershed scale	Mike-SHE Lumped cell structure	Not clearly described; a simplified water transfer model with limited cells	Minimize pumping costs, recharge, and water transport	Not clearly stated, penalty functions are included in the formulation
Pierce (2006); Pierce et al. (2006)	Quantifying Sustainable Yield	Local to Regional: Central Texas, Barton Springs aquifer	MODFLOW or an aggregated Systems Dynamics Model of the same system	Link to TABU global search algorithm and systems dynamics model of ancillary systems	Six Objectives defined with stakeholders Max water allocation and location of pumping; two	Pumping (location and rate) drought policy levels for alarm and critical stages

(continued)

Table 25.2 (continued)

Source	Problem	Scale	GW Simulation	Optimization & larger DSS	Objective function	Decision variables
					formulations for maximizing minimum spring flow; saturated thickness; total storage	Impervious cover and land use
Carrera-Hernandez and Gaskin (2006)	Spatially explicit groundwater modeling	Any	MODFLOW	Link to GRASS for geospatial groundwater modeling	Pure simulation capabilities	Not Applicable
Letcher (2005)	Water allocation for a watershed basin	Regional to Large:	Network-nodes linked with surface water sites	WaDSS based on ICMS Applied to Namoi & Gwydir River Basins, Australia	Max water allocation	Not clearly stated, but variable options
Recio et al. (2005)[a]	Link hydrogeologic model with econometric for agricultural decisions	Regional: Eastern Mancha aquifer, Spain	MODFLOW, possibly 3-D (not clear) steady state	GESMO	Land allocation for crops; Crop yield maximization	Pumping Head levels Electricity costs
Mysiak et al. (2005)	Water resource management (general)	Local to regional	Not specified	MULINO	Multi-criteria weighting applications	Varies
Lanini et al. (2004)	Participatory Integrated model for basin study	Local to regional: Herault Middle Valley, France	Lumped parameter model of socio-hydrosystem	(no optimization) Matlab/Simulink	No clear description; Stock and flow/ steady state system	Head – drawdown Pumping natural discharge

Quintana et al. (2005)[b]	Groundwater governance	Local to regional: Herault Middle Valley, France	Not clear, but indicates that a groundwater module included	GOUVERNe or TIDDD (Tool to Inform Debates, Dialogues & Deliberations)	Exploratory decision support with stakeholder participants	Not clearly defined
Fredrick et al. (2004)	Contaminant susceptibility	Local: single aquifer, NY	2-D Steady state AEM	(no optimization) Spatial indexing Drastic method	Minimize pollution potential	Water table levels Drastic scores
Aziz et al. (2003)	Optimization link for groundwater monitoring plans	Local: contaminant plume various sites	Linear regression for plumes, empirical data, and simplified models	MAROS	Minimize the number of sampling sites and frequency	Monitoring location and time
Fatta et al. (2002)	Landfill leachate impact	Local: Ano Liosia landfill, Greece	MODFLOW/MT3D	ECOSIM : Pilot version / local client–server architecture	Linked simulation models, GIS	No decision problem results reported
Nalbantis et al. (2002)[c]	Conjunctive use management	Regional: Athens, Greece	MODFLOW Multi-cell and Lumped parameter models	HYDRONOMEAS: Multi-reservoir system management	Stochastic optimization (limited solution algorithm description)	Pumping
Oxley et al. (2002)	Land degradation in the Mediterranean	Regional: Argolida, Greece Marina Baixa, Spain	MODFLOW	MODULUS DSS: 9 sub-models for integrated assessment modeling	Solution algorithm and specific objectives not defined: General problem environmental problem scopes	Mentions as possible: Crop choice subsidy change water management and others
Naveh and Shamir (2000)	Groundwater level management	Local: Hula Lake, Israel	MODFLOW with GMS	Spreadsheet model	Microsoft Excel solver optimization add-ins	head levels canal flow rates

(continued)

Table 25.2 (continued)

Source	Problem	Scale	GW Simulation	Optimization & larger DSS	Objective function	Decision variables
Demetriou and Punthakey (1999)	Sustainable groundwater management	Regional: Wakool, Murray Darling Basin Australia	MIKE SHE, 3-D flow	MIKE SHE No optimization	Scenario modeling	mainly crop and vegetation related defined with historic data for scenarios
Sophocleous and Ma (1998)	Saltwater intrusion (estimate parameters)	Local: Great Bend Prairie aquifer	3-D density dependent flow/ solute transport (SWIFT II)	Linear regression (forward, backward, stepwise)	Minimize saline intrusion	Hydraulic conductivities pumping rate Distance to – saline interface Layer thickness
McKinney et al. (1997)	GIS-based DSS for River Basin Management (prototype level)	Local to regional: Hypothetical	No groundwater component described	GAMs (General Algebraic Modeling system)	Maximize supply; downstream flow; Minimize salt concentrations; power; import sources	Not clearly stated
Latinopoulos et al. (1996)	Engineering supply & remediation	Small : Hypothetical	2-D Method of Characteristics (1 year)	Monte Carlo; Stochastic programming	sum of Total costs + risk	Broken into costs, failure risks, tolerance
Andreu et al. (1996)	River basin planning & operational management	Local and Regional:	Eigen value aquifer response flow module – Segura & Tagus basins, Spain	AQUATOOL	Not clearly stated	Not clearly stated
Datta and Peralta (1986)	Alternative selection (Surrogate Worth Tradeoff)	Regional: Grand Prairie, AR	2-D Steady state Flow	Dynamic Multi-objective optimization (Quadratic & Linear)	Min Cost of Water And Max total supply	Pump location & volume Head drawdown Vol. surface water diverted

Due to the nature of groundwater systems, decision problems for these resources tend to fall into the category of emergent decision contexts (i.e. problems that are ill-defined and lack a common heuristic for identifying solutions). Groundwater management problems will likely require the application of proactive support of science-based deliberation and negotiation DSS. Application of proactive DSS tools for real world groundwater cases are not reported, yet case studies demonstrate transitions from passive toward progressively more active use of DSS tools for groundwater problems. In the future, the field of groundwater decision support systems can be expected to evolve toward increasingly proactive type DSS.

25.5.2 Applications of Decision Support to Groundwater Cases

While distributed groundwater modeling approaches have advanced significantly, their incorporation in decision support processes remains limited, and the inclusion of groundwater cases within IAMs or participatory processes is largely absent. The following sections review the use of decision analytic techniques and decision support as reported in the literature for a range of groundwater problems, most frequently discussed in relation to health and environmental quality concerns. Risk assessment techniques have been applied to groundwater problems associated with petroleum spills, waste site leachates, agricultural contaminants, and radioactive materials control (Correll and Dillon 1993).

Control and management of groundwater supply is a primary topic in groundwater research and application, yet few DSS have been developed specifically to address this topic. An evaluation of decision-analysis with hydrogeological applications was put forth by Freeze et al. (Freeze and Massmann 1990; Freeze 1992) for project evaluation. Freeze's paper was timely, preceding the development of a wide-array of DSS for applications to groundwater, particularly contamination and remediation problems (Camara and Cardoso da Silva 1990; Xiang 1993; Lovejoy et al. 1997), but little work can be found applying the same concepts to aquifer yield. A few lumped system approaches without spatial considerations are reported (Naik and Awahthi 2003; National Research Council 1997), or with dimensional approximation (Miles and Chambet 1995), but these efforts lack the credibility of a distributed groundwater model that has been vetted scientifically. To address this issue, advances in linking groundwater with geospatial utilities are streamlining approaches for incorporating spatially detailed models (Carrerra-Hernandez and Gaskin 2006). Spatially-distributed models have been used for permitting and operation decisions while lumped-parameter models are typically used to evaluate socioeconomic relationships.

Sophocleous and Ma (1998) provide one of the earliest groundwater DSS that evaluates the impact of salt water intrusion on aquifer yield. Since 1997 interest in decision support applications has increased (Jamieson 1997). Table 25.2 presents a summary of the literature regarding decision applications and support systems related to groundwater management. Examples include articles that list specific tools or decision analysis applications, as well as integrated models for environmental decisions that include a groundwater component.

Groundwater decision support systems ought to be capable of providing alternative means for approaching water resource management operations through adaptive management for water resources. Table 25.2 also lists decision support and decision analysis projects reported in the literature with groundwater, environmental, optimization, multi-criteria analysis, and other relevant features.

The examples in Table 25.2 demonstrate progressively higher levels of sophistication in the integration of groundwater in DSS applications, yet groundwater DSS have attained primarily passive type DSS and active type cases are emerging. GESMO (Recio et al. 2005) incorporates a steady-state MODFLOW model to evaluate econometric problems for agricultural use on a regional scale. MIKE-SHE (Demetriou and Punthakey 1999) addresses the problem of sustainable groundwater management, but does not incorporate optimization techniques, and instead pure scenario modeling is used. Hydroanemas (Nalbantis et al. 2002) incorporates stochastic programming to address uncertainty and evaluate conjunctive use problems with an embedded MODFLOW model to simulate groundwater response. Gouverne (Quintana et al. 2005) focuses strictly on policy questions to date and incorporates the media-based input from stakeholder participants, but does not clearly describe the groundwater component of the system. WaDSS (Letcher 2005) addresses the problem of water resource distribution on a regional scale linking surface-water and groundwater through a nodal network.

To achieve proactive type guidance tools for DSS, computational advances in areas such as artificial intelligence, optimization algorithms, real-time sensing, informatics, and science visualization will be needed. In the case of groundwater, it is common for subject matter experts to pair models of groundwater response with optimization algorithms. Yet the most advanced algorithmic support remains limited to use by technical experts with particular emphasis on applications for parameterization of numerical models rather than DSS applications.

Development and advances of optimization techniques are integral to the potential for achieving advanced decision support applications. Reviews of optimization applications for groundwater management (Reed et al. 2013; Singh 2012) reveal that the use of traditional optimization and global search techniques have been applied to support decisions related to quantity and quality problems. For example, the groundwater decision support system (GWDSS) presents a hybridized example for water allocation that includes both simulation-optimization and lumped parameter modelling tools (Pierce 2006; Pierce et al. 2006). Artificial Neural Networks (ANN), such as the River GeoDSS (Triana et al. 2010) and Bayesian networks (Molina et al. 2013a, b; Fienen et al. 2013) present an advanced area of research that leverages algorithms to generate potential candidate solutions. The first report of an immersive environment is implemented for a case in the Sichuan Province, China demonstrating a framework that links virtual environments with models (Zhang et al. 2013). As the algorithms and computing capacity have advanced the problems and approaches have also evolved to increasing levels of complexity.

An important indicator of advances and maturity in the field of DSS applications to groundwater problems will be the replication and reuse of DSS methods and software application tools. The application of Bayesian networks (Moura et al. 2011; Molina et al. 2013a, b; Fienen et al. 2013) across multiple cases demonstrates a replicable methodology, and the WEAP-MODFLOW software tool (Le Page et al. 2012; Hadded et al. 2013) is gaining traction across several applications.

Tools and methods are emerging that provide more generalized approaches to DSS for groundwater with some cases shown in Table 25.2 that can be categorized as active type DSS. The pinnacle of applications for model mediated negotiation, or proactive DSS, will require continued advances in computation and algorithm support to identify tradeoffs and candidate solutions among the myriad of complex alternatives.

25.6 Factors Related to Adoption of DSS

The complex nature of groundwater resources often overwhelms decision-makers and inhibits the creation of clear management strategies. The possible number of management permutations can be almost innumerable, even for small scale aquifers, which in current accepted practice results in the inefficient evaluation of management alternatives. DSS can provide the computational tools and methodologies to address the complexity of groundwater problems.

Ideally a DSS will consider scientific knowledge, social process, operational constraints, as well as technology system performance. The potential to improve upon current groundwater management and policy practices through the use of science-based DSS is significant. Yet bridging the gaps to advance toward widespread adoption and usefulness of groundwater DSS requires explicitly addressing a myriad of factors (see also McIntosh et al. 2011), such as:

– Financial costs – because implementing a DSS system limits groundwater management districts frequently requires software licenses and staff or consultant time.
– Knowledge to implement – use of a DSS system requires the technical capacity to operate and use advanced software products.
– Adaptability of DSS – every decision situation has contextual elements and situation-specific considerations. DSS systems must be easy to adapt to each case before use.
– Multi-disciplinary team – the range of knowledge and expertise necessary to represent a groundwater problem can be very broad and requires expertise across domains.
– Adequate governance structures – without appropriate authority to manage the resources or infrastructure to support a DSS long-term the likelihood of adoption and use drops
– Trust – DSS deployment depends on trust among collaborators.

Groundwater systems frequently cross political boundaries, are exposed to multiple hazards, and affect a broad range of stakeholder groups. Before DSS can be expected to flourish in groundwater use there is the need to: (1) develop new tools that are increasingly transparent to the user groups; (2) improve the integration of tools into daily use by decision makers; and (3) continue collection of input parameter data and improve data measurement. Successful DSS for groundwater management will need to remain flexible and simple enough to explain to various user and decision-making groups while addressing key barriers to adoption.

25.7 Conclusions

Groundwater management involves both the facets of an aquifer's behavior as well as the preferences of its users. Users who presume sovereignty over their water rights and withdraw water to meet their individual social-economic needs without considering potentially adverse consequences to others may be following local allocation norms, even as they create the potential for disputes.

In order to address the projected future demands of society for fresh water, groundwater science must provide adequate characterization of the physical system to assure that policy limits for feasible allocation are achievable. Realistic projections of resource demand require incorporating the preferences of the community that depends upon that resource. The interdependency of community drivers and science-based analyses must be recognized and integrated in order to determine the actual availability of a resource under various management schemes.

DSS can provide a set of applications, methodologies, and tools to identify aquifer sensitivity, evaluate inter-relationships among parameters, test alternative management scenarios, and define levels for decision variables that can guide policy making and, ideally, reduce conflict over the resource.

Aquifer decision support is a multi-disciplinary field of study because it relies upon physical models of aquifer behavior, contemporary groundwater data collection systems, rapidly developing simulation and optimization software, as well as qualitative methods to engage and learn from resource users. While the idea of interactive, knowledge-based decision support for groundwater is straightforward, the combination of technical challenges, multi-disciplinary complexity, and scientific uncertainty create significant barriers to implementation. Today, decision support is experiencing a revival in many fields of interest, particularly land use planning and other physical science disciplines. Whether or not the field begins to take form in groundwater sciences will depend in large measure upon the ability of the theoretical techniques to live up to conceptual expectations of the users and the ability of researchers to link theoretical advances to practice.

To meet future water demand scenarios it will be necessary for groundwater aquifers to be managed more effectively and sustainably. Current methods used to determine groundwater allocation and management strategies are neither equitable nor efficient, frequently resulting in the over-abstraction of aquifer systems. Decision support systems (DSS) provide a means for water managers to evaluate complex data sets that include hydrogeologic, economic, legal and environmental elements to calculate available yield for aquifers or estimate levels of risk, resulting in improved policies for groundwater management that may, eventually, help ensure the long-term sustainability of water use by society. Water and humans are inextricably linked. As burgeoning human populations stress existing water resources, civilization needs to manage water. This need highlights the inseparable link between scientific knowledge and human interpretation of the environment. Societies interpret the state of the world around them, and take certain actions upon the physical systems based upon that interpretation. As resource constraints grow and the potential consequences of mismanagement increase, improved methods and DSS for people to convert information into knowledge are vital to ensure long-term resource stability.

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